Pilot-study of ridden walk on the circle – effects of progressive collection and lateral exercises

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Abstract

When collecting the horse, the rider influences stride length, forehand/hindquarters balance, and head-neck position. The study aim was to describe the vertical excursion of the withers and croup, and the sagittal cannon angles during collection and lateral exercises. Ten horses were ridden by five riders during 14 trials (1-5 per rider) on 10 m circles. Each trial included free walk, four degrees of increasing collection, and haunches-in and shoulder-in. Inertial measurement units (100 Hz) were positioned on the withers, the first sacral vertebra (S1) and laterally on the cannons. Data for each exercise were stride-split. Range of motion (ROM), minima and maxima were studied in mixed models, controlling for stride duration. S1 vertical ROM ranged between 30-32 mm (highest degree of collection) and 51 mm (free walk), significantly smaller with increasing collection. S1 ROM during the inside hind limb step was smaller in haunches-in and shoulder-in compared to at the lowest degree of collection. Withers ROM ranged between 12 mm (lowest degree of collection) and 16-18 mm (highest degree of collection). Fore cannon protraction-retraction ROM ranged between 57° (highest degree of collection) and 63° (free walk). Hind cannon protraction-retraction ROM ranged between 47-50° (highest degree of collection) and 51-56° (free walk). All limbs had significantly smaller ROM at the highest degree of collection. Cannon ROMs were smaller for the outer limbs in haunches-in, and all limbs but the outer fore in shoulder-in, compared to the lowest degree of collection. Progressively decreasing ROM for fore- and hind limb cannons and S1 suggest that the riders achieved a shortening of the gait at higher degrees of collection. In shoulder-in and haunches-in, the diagonal oriented in the direction of motion showed decreased hind limb cannon ROM while forelimb cannon ROM was maintained, which could suggest increased shoulder freedom and collection of the targeted diagonal.

Keywords: equine, kinematics, horse-rider interaction, haunches-in, shoulder-in

1. Introduction

The walk is a relatively slow four-beat symmetrical gait. With four separated hoof placements, minimum and maximum vertical positions of the fore- and hindquarters become out of phase. Compared to trot, equine walk has less frequently been investigated scientifically. There have been studies on dressage characteristics of walk (Clayton, 1995; Rhodin *et al.*, 2018; Weishaupt *et al.*, 2006) and horse movement on a circle or during turning (Chateau *et al.*, 2010; Egenvall *et al.*, 2020a; Hobbs *et al.*, 2011; Wakeling *et*

al., 2006). Protraction-retraction range of motion (ROM) was larger for outer compared to inner limbs when walking on a circle (Egenvall *et al.*, 2020a).

Theoretically, horses can be ridden with almost no rider influence, apart from the rider's weight, in all gaits. The most common example of limited influence is free walk on long reins. Alternatively, the rider may seek to actively influence the horse's gait to a varying degree, ultimately aiming to control how each step is executed. When the rider strives to 'collect the horse', the main aspects that the

rider aims to influence are the stride length, forward reach of the hind limbs, the forehand/hindquarters balance (to be less on the forehand), and the horse's head and neck position (in collection striving for the dorsum of the head to be vertical, with an arched neck with a relatively high poll). The hallmarks of collection described in equestrian texts are a decrease in stride length with retained energy of movement, increased flexion of the hind limb joints with lowering of the hindquarters, and increased protraction of the hind limbs (Branderup, 2001; De la Guérinière, 1729; Hess *et al.*, 2012). These movement pattern changes are claimed to result in a shift of weight from the forelimbs to the hind limbs. However, comparing horses ridden at free walk and collected walk, only 1% of the body weight was transferred to the hindquarters (Weishaupt *et al.*, 2006). Regarding kinematics, increased degree of collection in walk has been found to be associated with decreased stride length (Clayton, 1995). The stride frequency also decreased but to a lesser extent (Clayton, 1995). Increased flexion of the hock and stifle has been demonstrated (Rhodin *et al.*, 2018). Equestrian authors have suggested that during basic schooling, collected walk should be avoided and the horse should mainly be worked in a low head-neck position, either with light rein contact or on loose reins, because constraining the walk may lead to problems, e.g. irregular walk (Hess *et al.*, 2012). Collected walk can thus be considered a relatively difficult exercise for horses and riders.

During flatwork or dressage training horses are commonly ridden with lateral bending (Eisersjö *et al.*, 2015). The slightest degree is having just a little bend to the left or right at the horse's poll (in German 'stellung'); for example, riding along the perimeter of the arena horses will most often be asked for 'stellung' to the inside of the arena. A higher degree of lateral bending is used when riding on circles or performing lateral exercises, e.g. shoulder-in or haunches-in. In lateral exercises the horse is ridden on three (or four) tracks relative to the direction of motion, and the rider asks for one of the hind limbs to step more in under the horse's body (FEI, 2020), i.e. collecting one diagonal at a time. For example, in a left shoulder-in on three tracks the horse is bent to the left and the left hind limb should follow the track of the right forelimb; engagement of the left hind limb is a main focus of the exercise. Rider's leg forces and saddle pressure have been measured during lateral exercises at the trot (De Cocq *et al.*, 2010), to our knowledge the only study addressing lateral exercises.

The intention behind the current set-up was to study the biomechanics of various exercises in a realistic, yet reproducible, dressage training context. The aim of this pilot study was to examine vertical excursion of the withers and the croup, and sagittal cannon angles, during increasing degrees of collection and during lateral exercises (haunches-in and shoulder-in) in horses ridden in walk on

the circle. It was hypothesised that there would be a dose-response relationship between the degree of collection and both vertical midline and cannon ROM. It was further hypothesised that lateral exercises would show features similar to collection.

2. Materials and methods

Horses and their equipment

The experiment took place at one training facility, using horses that had been stabled there for at least 2 months. Data on breed, gender, age, withers height, and time with the owner were recorded for each horse (Table 1). All horses were trained in classical dressage since several years and were experienced in performing the exercises included in the study. The rider/trainer of the horse was asked a set of questions to appreciate sidedness during training and riding for each horse (Supplementary Table S1). The horses were deemed sound by a veterinarian (AE) who before the experiment watched the horses work for several sessions in walk and trot in the arena where the experiment took place. All the horses were deemed fit to perform the study protocol. The horses were equipped with their custom saddle (one horse was ridden bare-back) and head gear (Table 1). A cavesson was used for lunging and was kept on during riding; one horse was ridden bitless on the cavesson. According to Swedish law this study did not need specific ethical approval, neither for the participation of the riders nor the horses. Riders and horse owners provided written informed consent.

Riders and their equipment

One trainer (HE) and four of her students participated. The riders were female, aged 18, 20, 21, 49 and 57 years, with weights and heights ranging from 61–66 kg and 158–173 cm. All students had been training regularly with the trainer since at least 4 years. All riders considered themselves right-handed. All riders were accustomed to their mounts but varying from that they rode their own horses to that they had ridden the horse 5 times previously. Riders wore safety helmets and carried a dressage whip (rarely used during the experiment), while spurs were not used. Some horses were ridden by several riders (Table 1), but there was no intention to cross all horses and riders.

Design

The whole experiment comprised a sequence of exercises, which allowed the horses some warm-up in free walk without a rider and continued with progressive collection under rider. The horses were first measured walking straight in an alley on concrete, with equipment but without rider. The rest of the exercises were performed on a 10 m diameter circle that was prepared by drawing a perimeter trace on a soft

Table 1. Details on the 10 horses in the study.^{1,2}

Horse no.	Breed	Gender	Age (yrs)	Height at withers (cm)	Duration with owner (yrs)	Saddle	Bridle	Hollow side
1	Russian crossbred/PRE ³	Gelding	17	158	3	Acad saddle ⁴	Kimberwick, straight bar	Left
2	Lusitano	Gelding	11	150	2	Acad saddle	Snaffle, straight bar, D-rings	Right
3	Knabstrupper	Mare	11	155	7	Acad saddle	Baucher	Left
4	PRE	Mare	13	158	4	Acad saddle	Baucher	Left
5	Lusitano	Mare	16	154	10	Acad saddle	Curb bit	Neither
6	Newforest	Gelding	15	138	4	Bareback	Bitless, cavesson	Left
7	PRE	Mare	17	158	13	Acad saddle	Kimberwick, straight bar	Left
8	Lusitano	Mare	7	155	1	Acad saddle	Snaffle	Neither
9	PRE	Stallion	11	153	10	Acad saddle	Snaffle with eggbutt rings	Right
10	PRE/Frederiksborg horse	Mare	11	158	11	Acad saddle	Kimberwick, straight bar	Right

¹ Rider 1 rode horse 1, 2, 5, 7 and 9, rider 2 horse 3 and 4, rider 3 horse 1, 2, 5 and 10, rider 4 horse 6, and rider 5 horse 6 and 8.

² Hollow side is evaluated from Supplementary Table S1.

³ PRE = pura raza Española.

⁴ Acad saddle = academic leather tree saddle.

sand-fibre surface in an indoor arena. The horses were first lunged in freely moving walk without rider a few circles to the left and to the right (initial lunging direction, left/right, was alternated between measurement days). Directly after this the rider mounted. Beginning in the opposite direction compared to lunging, the rider performed the following walk exercises: free walk on long reins ('free walk'); gently framing the horse between the seat, upper legs and hand, but not using rein or seat aids actively ('neutral seat'); adding a light half-halt during inside hind limb stance asking the horse for some collection ('neutral seat with one half-halt'); performing a light half-halt during each hind limb stance, asking for more collection ('neutral seat with double half-halts'); and finally at full collection where the riders strived to maintain their pelvis caudally rotated, limiting pelvic pitch through the whole stride, asking the horse for as much collection as the horse was able to perform ('full seat'). Neutral seat was then adopted again and haunches-in and shoulder-in were performed. The riders were allowed to alternate between haunches-in and shoulder-in until a successful attempt was recorded for each of these. This was followed by some strides in neutral seat ('neutral seat aft') and about one circle in free walk ('free walk aft'). The ridden exercises were then repeated in the other direction. Only data from the ridden exercises were used in the current analysis. The riders, and the trainer, evaluated the exercises out loud during the ride, to aid in later extraction of the best performed part of each exercise based on the video recordings.

Equipment

Inertial measurement unit (IMU) sensors (x-io Technologies Limited, Bristol, UK) were positioned on the withers, the croup and laterally on the canons of all four limbs (Figure 1);

for midline sensors linear acceleration was positive upwards, and for cannon sensors pitch was positive for clockwise rotation as seen from the horse's left side, i.e. equivalent to protraction (other IMU-recorded data not used in the study). IMU size was 56×39×18 mm, weight 46 g and with 16-bit resolution. The sampling rate was set to 100 Hz. The IMU sensors were synchronised using dedicated software (<https://x-io.co.uk/ngimu/>). The experiments were video-recorded (Sony FDR-AX53, Tokyo, Japan) at 25 Hz. When recording trials on the circle the camera was positioned in the middle of the circle. To synchronise the video and the measurements, the IMU sensors were tapped (all positioned on a chair) in front of the camera just after starting and before turning the sensors off.

Figure 1. Study horse with equipment and tack. The withers sensor is placed in front of the saddle, the S1 sensor on the croup and cannons sensors are placed laterally. (The saddle cloth is placed to the rear to avoid interference with the withers sensor.)

Data analysis

The videos were scrutinised. The seconds with the 'best-executed' sequences were recorded for each exercise and direction by author AE. When selection was difficult this was resolved in consensus with author AB. Data for the selected sequences were split in steps and strides based on maximum protraction of the hind limbs and were visually inspected before inclusion. Step and stride normalised (to 100 points) data curves were plotted for visualisation. For the vertical position of the withers and S1, ROM was calculated from step-normalised data. For cannon sagittal angles, ROM and values for and timing of maximum protraction and retraction, were calculated from stride-normalised data. For timing of forelimb cannon maximum retraction, timing values >90% were subtracted by 100. This was done in order for all timings to be expressed relative to the beginning of the stride.

Statistics

Descriptive and analytical statistics were made using SAS (SAS Institute Inc., Cary, NC, USA). S1 and withers step data and cannons stride data were analysed in mixed models (proc MIXED). Stride duration (in s) was entered as a fixed linear effect in all models, after having verified that a linear fit was a reasonable assumption. The general random parameter structure consisted of rider, horse, rider-horse combination and specific exercise (e.g. free walk in left direction) within rider-horse combination. The SAS-option pdiff was used for calculating least square means and for follow-up testing of selected pairwise comparisons. The *P*-value limit for statistical significance was set to <0.05. *P*-values were not adjusted for multiple comparisons.

The following two groups of models were created:

1. Models were constructed from step-normalised data, with ROM for the vertical displacement of the withers and of S1 as dependent variables. Each observation was labelled as an inside or outside hind limb step. Fixed categorical effects were step (inside or outside), exercise (ignoring direction) and the two-way interaction between step and exercise. Comparisons were made between (a) progressively increasing degree of collection, (b) neutral seat and each of the collected exercises, (c) neutral seat and lateral exercises, and (d) free walk in the beginning versus after exercise. Comparisons were made within step (inside/outside).
2. Models were constructed from stride-normalised data, with cannon ROM, and minima and maxima and their timing, as dependent variables. Fixed categorical effects were limb (inner fore, outer fore, inner hind, outer hind) and exercise, including the two-way interaction between

limb and exercise. In this analysis, exercise sequences with data for only stride were excluded. Principally the same pairwise comparisons were made as for model 1.

3. A model with stride duration as outcome was created, with the same general random effects as above. Fixed effects were exercise and hind limb cannon ROM (the left limb value was used), the latter was graphically checked for linearity vs stride duration.
4. Subjective laterality was tested upon the withers, S1 and cannon ROM models as an interaction with inside/outside step (withers and S1 models) or limb (cannon model). Hollow side (left/right) was tested in two variants (in separate models). The horses denoted as 'neither' were either categorised as left (one model) or right-lateralised (one model, Table 1), because some horses could not be clearly evaluated as left or right-lateralised.

To achieve normality of residuals the following steps were taken. If variable means and medians were close, standard deviations relatively small and skewness and kurtosis close to zero, variables were analysed in untransformed formats. If this was not the case variables were Box Cox transformed and the best practical transformation for each variable was adopted. Residual plotting was employed in the last step to evaluate whether residuals were normally distributed (not ideal for the cannon timing variables).

3. Results

From placing the sensors until their removal each trial took 35–50 min. The number of strides and trials per exercise are shown in Supplementary Table S2 (e.g. only 12 of 14 trials had data on 'free walk aft'). One horse (in one trial) had synchronisation failure for S1 data, hence S1 analyses included 9 horses (13 trials). For 21 exercise sequences only one stride was retained for analysis, nine of these were for lateral exercises. In general, there were somewhat more strides included for free walk compared to the other exercises (Supplementary Table S2). Stride duration increased progressively with collection (Table 2).

Figure 2 and Supplementary Figure S1 show examples of time-normalised traces of withers and S1 vertical displacement and Supplementary Figure S2 shows cannon pitch (upper graphs outer hind and inner fore, lower graphs inner hind and outer fore), all from the same horse. It is evident that the withers traces, over the course of the exercises, were more irregular than the other parameters. The same was observed for all the horses in the study.

Supplementary Results S1 contains model output, data and SAS-code for all models. All models except withers and S1 ROM were analysed untransformed.

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Table 2. Least square means estimates (Est) and standard errors (SE) reported by exercise for the model with stride duration (s) as outcome (n=1,714 strides, from 10 horses during 14 trials).

Exercise	Est	SE	Selected comparisons ¹
Free walk	1.299	0.050	
Neutral seat (NS)	1.357	0.050	
NS one half-halt	1.417	0.050	
NS double half-halt	1.462	0.050	
Full seat	1.578	0.050	
Haunches-in	1.410	0.050	
Shoulder-in	1.393	0.050	
NS after exercise	1.376	0.050	
Free walk after exercise	1.313	0.050	

¹ Grey comparisons are non-significant ($P>0.05$), black $0.01<P<0.05$ and magenta $P<0.01$.

Withers ROM

The exercise $\times$ step interaction was significant at $P<0.0001$ and stride duration was significant at $P=0.001$ (least square means for the different exercises were calculated at grand mean stride duration). Withers ROM increased with increasing stride duration (positive coefficient 0.26 (standard error (SE) = 0.08) on the logarithm-transformed scale). Withers ROM ranged between 12 mm (low degree of collection) and 18 mm (outside hind limb step in full seat, Table 3). It should be noted that the inside hind limb step, the period from inner hind limb maximum protraction to outer hind limb maximum protraction, includes first a withers maximum related to midstance of the outer forelimb and then a withers minimum at inner forelimb early stance, and *vice versa* for the outside hind limb step.

Figure 2. Time-normalised stride data (single strides in red, mean of all strides in blue) for the withers vertical displacement by exercise, in left (upper row) and right (bottom row) directions on the circle (horse 2, trial 2). 0-100% of the stride (x-scale) is relative to inner hind limb maximum protraction.

Figure 2. Continued. Time-normalised stride data (single strides in red, mean of all strides in blue) for the withers vertical displacement by exercise, in left (upper row) and right (bottom row) directions on the circle (horse 2, trial 2). 0–100% of the stride (x-scale) is relative to inner hind limb maximum protraction.

Comparing increasing degrees of collection (a and b comparisons), the highest withers ROM estimate was found for the highest degree of collection. Comparing lateral exercises to neutral seat, withers ROM was higher for the inside step in haunches-in and both steps in shoulder-in. Comparing free walk before and after the other exercises, withers ROM was increased after.

S1 ROM

For S1 ROM the exercise $\times$ step interaction was significant at $P=0.02$ and stride duration was significant at $P<0.0001$. S1 ROM decreased with increasing stride duration (negative coefficient, -0.073 (SE = 0.005) on the square-root transformed scale).

S1 ROM ranged between 30 mm (outside step in full seat) and 51 mm ('free walk aft', Table 4). Several significant

comparisons indicated that increased degree of collection was associated with smaller S1 ROM (for both inside and outside steps). Inside step S1 ROM in haunches-in, as well as inside step S1 ROM in shoulder-in, were smaller compared to neutral-seat (c) haunches-in. Comparing free walk before and after (d), 'free walk aft' had larger S1 ROM compared to free walk at the beginning, for both inside and outside steps.

Canon ROM, protraction and retraction

For cannon ROM the exercise $\times$ limb interaction was significant at $P<0.0001$ and stride duration was significant at $P<0.0001$. The stride duration estimate was -6.53 (SE = 0.65), suggesting that cannon ROM decreased with increasing stride duration. For maximum protraction, the exercise $\times$ limb interaction was significant at $P=0.0002$ and stride duration was non-significant at $P=0.16$. For

Table 3. Results and comparisons for the withers range of motion model.¹

Exercise	Step	Est	SE	BT	a. Increasing collection	b. Neutral to collection	c. Neutral to lateral	d. Before and after
Free walk	inside	-4.41	0.09	12.1				
	outside	-4.46	0.09	11.6				
Neutral seat (NS)	inside	-4.36	0.09	12.8				
	outside	-4.45	0.09	11.7				
NS one half-halt	inside	-4.32	0.09	13.3				
	outside	-4.37	0.09	12.6				
NS double half-halt	inside	-4.19	0.09	15.1				
	outside	-4.29	0.09	13.7				
Full seat	inside	-4.14	0.10	15.9				
	outside	-4.03	0.10	17.7				
Haunches-in	inside	-4.19	0.09	15.2				
	outside	-4.28	0.09	13.9				
Shoulder-in	inside	-4.23	0.09	14.5				
	outside	-4.23	0.09	14.6				
Free walk after exercise	inside	-4.31	0.09	13.5				
	outside	-4.28	0.09	13.8				

¹ Least square means (Est) with standard errors (SE) on the logarithm-transformed scale (original scale in m), back-transformed least square means (BT in mm), and evaluated pairwise comparisons (n=3,526 steps, from 10 horses in 14 trials). Grey comparisons are non-significant ($P \geq 0.05$), black ($0.01 < P < 0.05$) and magenta ($P \leq 0.01$).

Table 4. Results and comparisons for the S1 range of motion model.¹

Exercise	Step	Est	SE	BT	a. Increasing collection	b. Neutral to collection	c. Neutral to lateral	d. Before and after
Free walk	inside	0.217	0.004	47.0				
	outside	0.215	0.004	46.1				
Neutral seat (NS)	inside	0.202	0.004	40.8				
	outside	0.203	0.004	41.2				
NS one half-halt	inside	0.192	0.005	36.7				
	outside	0.191	0.005	36.6				
NS double half-halt	inside	0.182	0.005	33.1				
	outside	0.184	0.005	33.9				
Full seat	inside	0.179	0.005	31.9				
	outside	0.174	0.005	30.1				
Haunches-in	inside	0.188	0.005	35.2				
	outside	0.188	0.005	35.4				
Shoulder-in	inside	0.197	0.005	38.8				
	outside	0.195	0.005	38.1				
Free walk after exercise	inside	0.226	0.005	50.9				
	outside	0.225	0.005	50.8				

¹ Least square means estimates (Est) with standard errors (SE) on the square-root transformed scale (original scale in m), back-transformed estimates (BT in mm) and evaluated pairwise comparisons (n=3,471 steps, from 9 horses in 13 trials). Grey comparisons are non-significant ($P \geq 0.05$), black ($0.01 < P < 0.05$) and magenta ($P \leq 0.01$).

maximum retraction, the exercise × limb interaction was significant at $P<0.0001$ and stride duration was significant at $P<0.0001$. The stride duration estimate was 5.56 (SE = 0.66) suggesting that a longer stride duration was associated with a larger (less negative) maximum retraction angle, i.e. decreased cannon retraction.

Forelimb cannon pitch ROM ranged between 57° (both forelimbs in full seat) and 63° (both forelimbs in ‘free walk aft’, Table 5). Hind limb cannon pitch ROM ranged between 47° (inner hind in full seat) and 56° (outer hind in free walk both before and after exercises). Forelimb maximum protraction varied between 16° (outer fore in full seat) and 21° (inner fore in ‘free walk aft’), and hind limb maximum protraction between 34° (inner hind ‘neutral seat with

double half-halts’ and full seat) and 39° (outer hind in both free walk categories) (Table 6). Forelimb maximum retraction varied between -40° (inner fore in ‘neutral seat with double half-halts’ and full seat) and -43° (outer fore in ‘free walk aft’), and hind limb maximum retraction between -13° (inner hind full seat) and -17° (outer hind in both free walk categories) (Table 7). A number of significant comparisons indicated that cannon ROM decreased with increasing collection. Correspondingly, several significant differences (involving all four limbs) between higher degrees of collection and neutral seat indicated that maximum protraction was the smallest in higher degrees of collection (Table 6). Maximum retraction (Table 7) of both hind limbs was reduced in full seat compared to neutral seat.

Table 5. Results and comparisons for the cannon range of motion model.¹

Exercise	Limb	Side	Est	a. Increasing collection	b. Neutral to collection	c. Neutral to lateral	d. Before vs after
Free walk	F	in	61.1				
		out	61.7				
	H	in	51.3				
		out	55.6				
Neutral seat (NS)	F	in	60.6				
		out	60.6				
	H	in	50.1				
		out	53.8				
NS one half-halt	F	in	59.1				
		out	59.3				
	H	in	48.9				
		out	53.0				
NS double half-halt	F	in	57.8				
		out	58.4				
	H	in	48.3				
		out	51.2				
Full seat	F	in	56.6				
		out	57.2				
	H	in	46.7				
		out	49.6				
Haunches-in	F	in	59.4				
		out	58.1				
	H	in	49.2				
		out	50.5				
Shoulder-in	F	in	58.4				
		out	59.9				
	H	in	48.4				
		out	52.5				
Free walk after exercise	F	in	63.1				
		out	62.9				
	H	in	52.0				
		out	55.9				

¹ Least square means estimates (Est) in degrees and evaluated pairwise comparisons (n=6,772 strides, from 10 horses in 14 trials). The standard error is 1.1 degrees for all estimates. Grey comparisons are non-significant ($P\geq0.05$), black ($0.01<P<0.05$) and magenta ($P\leq0.01$).

Table 6. Results and comparisons for the maximum cannon protraction motion model.¹

Exercise	Limb	Side	Est	a. Increasing collection	b. Neutral to collection	c. Neutral to lateral	d. Before vs after
Free walk	F	in	20.3				
		out	20.2				
	H	in	36.9				
		out	38.9				
Neutral seat (NS)	F	in	19.6				
		out	18.9				
	H	in	35.7				
		out	38.3				
NS one half-halt	F	in	18.6				
		out	17.8				
	H	in	35.0				
		out	37.9				
NS double half-halt	F	in	18.1				
		out	17.4				
	H	in	34.3				
		out	36.6				
Full seat	F	in	16.7				
		out	16.1				
	H	in	34.2				
		out	35.8				
Haunches-in	F	in	18.9				
		out	16.4				
	H	in	35.7				
		out	37.1				
Shoulder-in	F	in	17.8				
		out	18.0				
	H	in	35.1				
		out	37.1				
Free walk after exercise	F	in	21.4				
		out	20.4				
	H	in	36.9				
		out	39.3				

¹ Least square means estimates (Est) in degrees and evaluated pairwise comparisons (n=6,772 strides, from 10 horses in 14 trials). The standard error is 1.1 degrees for all estimates. Grey comparisons are non-significant ($P \geq 0.05$), black ($0.01 < P < 0.05$) and magenta ($P \leq 0.01$).

Comparing cannon ROMs (Table 5) in lateral exercises and in neutral seat (c), ROMs were generally smaller for the lateral exercises. Maximum protraction became smaller for the inner fore in shoulder-in and the outer fore in haunches-in (Table 6). Maximum retraction of the outer hind became smaller in haunches-in (Table 7). Comparing free walk to 'free walk aft' cannon ROMs in 'free walk aft' were slightly larger for three of four limbs (Table 5).

Timing of cannon maximum protraction and retraction

For timing of cannon maximum protraction, the exercise $\times$ limb interaction was significant at $P < 0.0001$ and stride duration was non-significant at $P = 0.22$. Time of maximum

protraction varied between 28% of the stride (free walk) and 31% of the stride (full seat, shoulder-in) for the inner forelimb and between 76% (full seat) and 80% (neutral seat) for the outer forelimb. Maximum protraction occurred at $\sim 0\%$ for the inner hind limb (stride start defined from this event), and varied between 47% (free walk and shoulder-in) and 49% (full seat) for the outer hind limb (Table 8). Collection influenced the outer forelimb only, for which maximum protraction occurred earlier with increased collection. Comparing neutral seat and lateral exercises, outer forelimb maximum protraction occurred earlier in shoulder-in. Inner forelimb maximum protraction occurred later in 'free walk aft' than in free walk at the beginning.

Table 7. Results and comparisons for the maximum cannon retraction model.¹

Exercise	Limb	Side	Est.	a. Increasing collection	b. Neutral to collection	c. Neutral to lateral	d. Before vs after
Free walk	F	in	-41.1				
		out	-41.3				
	H	in	-14.7				
		out	-16.5				
Neutral seat (NS)	F	in	-41.1				
		out	-41.7				
	H	in	-14.6				
		out	-15.5				
NS one half-halt	F	in	-40.6				
		out	-41.5				
	H	in	-13.9				
		out	-15.0				
NS double half-halt	F	in	-39.7				
		out	-41.0				
	H	in	-14.0				
		out	-14.7				
Full seat	F	in	-40.0				
		out	-40.9				
	H	in	-12.8				
		out	-13.6				
Haunches-in	F	in	-40.4				
		out	-41.9				
	H	in	-13.5				
		out	-13.6				
Shoulder-in	F	in	-40.7				
		out	-41.9				
	H	in	-13.5				
		out	-15.4				
Free walk after exercise	F	in	-41.6				
		out	-42.5				
	H	in	-15.1				
		out	-16.7				

¹ Least square means estimates in degrees and evaluated pairwise comparisons (n=6,772 strides, from 10 horses in 14 trials). The standard error is 1.1 degrees for all estimates. Grey comparisons are non-significant ($P \geq 0.05$), black ($0.01 < P < 0.05$) and magenta ($P \leq 0.01$).

For timing of cannon maximum retraction, the exercise $\times$ limb interaction was significant at $P < 0.0001$ and stride duration was significant at $P < 0.0001$. The estimate for stride duration was 8.60 (SE = 1.07). Time of maximum retraction varied between 4% (free walk) and 9% (full seat, haunches-in and shoulder-in) for the inner forelimb, and between 55% ('free-walk aft') and 61% (full seat) for the outer forelimb. Time of maximum retraction varied between 66% (free walk) and 69% ('neutral seat with double half-halts' and haunches-in) for the inner hind limb, and between 15% ('free walk aft') and 19% (full seat) for the outer hind limb (Table 9). Both forelimbs and the outer hind limb reached maximum retraction later at high degree of collection compared to neutral seat. Maximum retraction of the

inner fore occurred later in haunches-in and shoulder-in compared to in neutral seat. Maximum retraction of the inner fore occurred later in 'free-walk aft' compared to free walk at the beginning.

Laterality

Hollow side and its interaction with inner/outer step or limb were tested upon the full ROM models, the interaction being significant for withers ROM ($P = 0.01$, significant using one of two variant variables) and S1 and cannon ROM ($P < 0.0001$). However, relevant comparisons, e.g. the hollow side as inner side vs the stiffer side as inner side, were all associated with large P -values (Supplementary Results S1).

Table 8. Results and comparisons for timing of maximum cannon protraction model.¹

Exercise	Limb	Side	Est	a. Increasing collection	b. Neutral to collection	c. Neutral to lateral	d. Before vs after
Free walk	F	in	28.1				
		out	78.7				
	H	in	-0.4				
		out	47.4				
Neutral seat (NS)	F	in	29.3				
		out	79.7				
	H	in	-0.3				
		out	47.9				
NS one half-halt	F	in	30.0				
		out	77.0				
	H	in	-0.4				
		out	48.1				
NS double half-halt	F	in	29.1				
		out	76.6				
	H	in	-0.8				
		out	48.6				
Full seat	F	in	30.7				
		out	76.1				
	H	in	-0.5				
		out	49.1				
Haunches-in	F	in	28.8				
		out	79.0				
	H	in	-0.5				
		out	48.6				
Shoulder-in	F	in	31.1				
		out	77.3				
	H	in	-0.4				
		out	47.2				
Free walk after exercise	F	in	30.5				
		out	77.2				
	H	in	-0.4				
		out	47.8				

¹ Least square means estimates (Est) in percent of the stride and evaluated pairwise comparisons (n=6,772 strides, from 10 horses in 14 trials). The standard error is 0.8% for all estimates. Grey comparisons are non-significant ($P \geq 0.05$), black ($0.01 < P < 0.05$) and magenta ($P \leq 0.01$).

4. Discussion

In this exploratory study, progressively increasing degree of collection, and lateral exercises, were studied in walk on the circle. Working the horse on a circle is common in horse training, and horses are frequently ridden with some degree of lateral bending (Eisersjö *et al.*, 2015). Considering that the walk is a symmetrical gait, maximum cannon protraction of the outer hind limb can be expected to occur at 50% of the stride relative to maximum protraction of the inner hind. However, maximum outer hind protraction was found to occur between 47 to 49% depending on exercise, reflecting a circle-induced asymmetry (Egenvall *et al.*, 2020a). Maximum forelimb protraction occurred

in-between these events, at 28 to 31% for the inner, and at 76 to 80% for the outer. The asymmetry in limb protraction-retraction. Protraction-retraction ROM for outer fore- and hind limbs, and maximum protraction of the outer hind limb, were found to be larger compared to the respective inner limb (Egenvall *et al.*, 2020a), and the outside pair of limbs were also found to have longer stride length (Hobbs *et al.*, 2011), in horses walking in 10 m circles on soft surface. In the current study, the effects of collection were similar for the inner and outer limbs.

Cannon protraction-retraction ROM generally decreased significantly with increasing degree of collection, for both

Table 9. Results and comparisons for the timing of maximum cannon retraction model.¹

Exercise	Limb	Side	Est	a. Increasing collection	b. Neutral to collection	c. Neutral to lateral	d. Before vs after
Free walk	F	in	4.0				
		out	54.7				
	H	in	66.3				
		out	15.6				
Neutral seat (NS)	F	in	5.6				
		out	56.3				
	H	in	67.3				
		out	16.7				
NS one half-halt	F	in	6.9				
		out	57.7				
	H	in	67.7				
		out	17.1				
NS double half-halt	F	in	6.8				
		out	58.3				
	H	in	68.5				
		out	17.8				
Full seat	F	in	8.8				
		out	60.6				
	H	in	68.4				
		out	18.8				
Haunches-in	F	in	9.0				
		out	56.5				
	H	in	68.5				
		out	17.6				
Shoulder-in	F	in	9.2				
		out	54.2				
	H	in	67.6				
		out	15.9				
Free walk after exercise	F	in	7.2				
		out	54.0				
	H	in	65.6				
		out	14.5				

¹ Least square means estimates (Est) in percent of the stride and evaluated pairwise comparisons (n=6,772 strides, from 10 horses in 14 trials). The standard error is 0.9-1.0% for all estimates. Grey comparisons are non-significant ($P \geq 0.05$), black ($0.01 < P < 0.05$) and magenta ($P \leq 0.01$).

fore- and hind limbs, and both inner and outer limbs. In earlier research, forelimb cannon ROM decreased with 6% and hind limb cannon ROM with 5% going from medium to collected walk (Clayton, 1995). Our figures going from neutral seat to the highest degree of collection (full seat) were 3-4%. Along with decreased cannon ROM, maximum protraction became smaller with increasing collection for both inner and outer fore- and hind limbs. The latter has also been found in previous studies of collection in walk on the straight (Clayton, 1995; Rhodin *et al.*, 2018). For the inner and outer hind limbs, maximum retraction was also decreased at the highest degree of collection, again in line with previous studies comparing collected vs less collected walk (Clayton, 1995; Rhodin *et al.*, 2018). In summary,

the horses in the current study showed similar features in collection compared to findings in previous studies. This confirms that collection has distinct kinematic features, and these appear to be comparably consistent between circle and straight line.

Croup vertical ROM became progressively smaller as the horses in the current study became more collected, concurrent with a decrease in hind limb cannon ROM. This association can be expected from the geometry of an inverse pendulum model, hence it is not unique to collection per se. ‘To put the horse on the haunches,’ is an early term for collection (Newcastle, 1658; Xenophon, 350 BC), which would imply that the croup should be lowered, possibly

concurrent with a smaller ROM. Measurements of the actual height of the croup is not possible with IMU-technique, but previous studies found no significant decrease in croup height in collection, neither in walk nor in trot (Rhodin *et al.*, 2009, 2018). However, collection can feature increased angulation of the pelvis (Rhodin *et al.*, 2009, 2018), which lowers the base of the tail if croup height is constant. Other features of collection described in equestrian texts include a decrease in stride length with retained energy of movement (Branderup, 2001; De la Guérinière, 1729; Hess *et al.*, 2012). It is further stated that the tempo should not decrease in collection (FEL, 2020), i.e. stride duration should not increase. Stride length, speed and stride duration are basic characteristics of a gait. They influence most kinematic variables, in addition to being interrelated. Collection entails a decrease in speed, making it challenging to study the effects of collection separate from those of speed. In the current study, stride duration did increase significantly with increasing collection, in line with a previous study (Clayton, 1995). Stride length and speed generally decrease with collection in walk while stride duration increases (Clayton, 1995). However, cannon protraction-retraction ROM was significantly reduced in collection despite correcting for stride duration in (all) the statistical models. Stride duration was used as an indicator for speed, since speed could not be measured with the IMUs. This finding would suggest that protraction-retraction ROM decreased more than can be expected from the decrease in stride duration alone. It could even be discussed if controlling for stride duration is preferable to controlling for speed, since a decrease in stride duration is not considered a genuine feature of collection. The collection we studied was performed during training, where exercises may be performed differently to at competition, regarding intensity and duration. Comparing our findings with the competition rules or the equestrian literature, it must also be noted that equestrian masters have formulated their biomechanical descriptions from sight, hearing and feel, and whether the equestrians meant the same (or different) things using one word (or another) in a specific situation is impossible to verify. Consequently, the features we and other researchers have measured may not be those that the equestrians looked at, and the question of agreement cannot be definitely answered.

In a haunches-in the rider asks the horse to place the outside hind limb closer to the midline, and in a shoulder-in it is instead the inside hind limb that should be placed closer to the midline (Hess *et al.*, 2012; Steinbrecht, 1886). This means that the forehand and hindquarters are displaced laterally in relation to each other, such that one diagonal pair of limbs are oriented to more in the intended direction of motion. However, each of the two exercises targets a different diagonal. This can be expected to result in movements asymmetries between forelimb and hind limb pairs, respectively, in the same way that moving on a curved track, e.g. a circle, creates asymmetries between

inside and outside limbs. Such asymmetries were indeed found in the current study, though the interpretation requires some consideration, since these were overlaid on the asymmetries caused by moving on a circle. Important goals of lateral exercises are to increase weight carriage by the hindquarters, and to increase shoulder freedom (Hess *et al.*, 2012; Steinbrecht, 1886). Our results suggest that these goals were reached to some degree for the respective targeted diagonals. The lateral exercises showed some of the same features as the collected exercises, but not to the same degree for both inner and outer limbs/steps. In shoulder-in, inner hind limb cannon ROM was smaller, and in haunches-in the outer hind had smaller ROM and decreased retraction, compared to neutral seat. In shoulder-in, ROM and protraction were reduced for the inner fore but not for the outer fore, and in haunches-in, ROM and protraction were reduced for the outer fore but not for the inner fore. Decreased cannon ROM was observed with increasing collection in the current study and decreased hind limb retraction has been shown previously to be a feature of collection comparing working or collected trot to passage and piaffe (Holmström *et al.*, 1995; Weishaupt *et al.*, 2009). Similarly, metatarsal retraction decreased from extended to collected walk (Clayton, 1995). Collection is a prerequisite for the lateral exercises (Hess *et al.*, 2012; Steinbrecht, 1886), and performing lateral exercises should also increase the horse's degree of collection (Hess *et al.*, 2012). Looking at midline variables, lateral exercises showed additional similarities to the collected exercises: S1 ROM decreased during both inside and outside steps in both exercises, and withers ROM tended to increase. Taken together, these findings suggest that the lateral exercises were indeed collected and/or had a collecting effect on the targeted hind limb. The retained ROM and protraction of the diagonal forelimb, despite a shortening of the hind limb gait, may reflect what equestrians describe as increased shoulder freedom.

S1 ROM, withers ROM and cannon pitch ROM all reached their highest values in free walk after the other exercises. This suggests that there was a warming-up effect of going through the trial. The horses seem to have walked with a longer stride length after the other exercises compared to before, perhaps from being more relaxed and supple. Since the complete sequence of ridden exercises was performed in each direction, before changing, it is not clear to what extent this warming-up effect occurred after work in only one direction or if both directions were needed for full effect. The cumulative effect of different exercises would be an interesting topic for further research, but it was outside the scope of the current study to elucidate this further.

Comparing our results to previous studies that have measured cannon pitch using high-speed video, stride curve shapes and approximate ROM are in agreement (Clayton, 1995; Hodson *et al.*, 2000, 2001). In horses ridden

on treadmill in a collected posture (neck raised, poll high and bridge of the nose slightly in front of the vertical), forelimb protraction-retraction stride ROM was found to be 56° and hind limb stride ROM 40° (Rhodin *et al.*, 2018), using the hoof and the elbow joint and fifth lumbar vertebra (L5), respectively, as reference points (also high-speed video data). For the most collected exercise, our least square means for cannon ROM were 57° and 47-50° for fore- and hind limbs, respectively. Compared to Rhodin *et al.* (2018), our figures are similar for the forelimbs and slightly larger for the hind limbs. Forelimb cannon maximum retraction occurs in-between forelimb lift-off and maximum flexion of the carpal joint (which occurs at ~70% of the stride, (Hodson *et al.*, 2000)), i.e. cannon retraction continues as the forelimb flexes during protraction. This implies that we should have found larger forelimb protraction-retraction ROMs compared to Rhodin *et al.* (2018), but this was not the case. Our mixed group of horses, predominantly of Iberian breed, may have contributed to differences between the two studies (Cano *et al.*, 2001), but the differences may also reflect circle-induced effects.

Withers ROM varied between 12-18 mm and S1 ROM between 30-51 mm. In a previous study on straight line walk mean ROM was considerably higher: 36 mm for the withers and 73 mm for L5 when horses were walking with a free head and neck position (Rhodin *et al.*, 2018). One reason for the lower values in the current study could be that our horses were somewhat smaller. Another reason is that displacements derived from IMU sensors are the result of double integration from accelerations, rather than measured directly. Looking at our data graphically, the regular curve shape of S1 vertical motion can be contrasted to the more irregular withers trajectory (Figure 2 and Supplementary Figure S1). We have earlier demonstrated, using IMU-data from the same experiment, that when rider weight is added to the horse on the circle, the 'original/inherent' biphasic withers vertical motion pattern of the walk will often change to an irregular pattern with higher frequency components (Egenvall *et al.*, 2020a). The reason for this is uncertain. A possible reason would be interference from the saddle, though that does not explain why the traces were comparably less irregular in free walk compared to in collection. Comparing the withers trajectory characteristics to high-speed video recordings of seven horses ridden and unriden in walk on a (straight) treadmill (Egenvall *et al.*, 2020b), similarities can be seen between the current IMU data and high-speed video data from some of the horses. We are somewhat unsure to what extent the withers data we recorded reflect true withers motion. Considering findings in previous studies of straight-line walk, but at the same time also including a possible circle effect, it is difficult to tell. Interference from the saddle cannot be excluded, maybe in combination with the rider's weight and/or the horse's head-neck position, being influenced by the rider through the collecting exercises. However, withers motion

per se also changes with a rider (Egenvall *et al.*, 2020b). We have deemed that ROM values can be used, but at the same time we felt it was important to clearly express that the data quality could potentially be substantially worse than for other parameters.

The study material was collected from one trainer, whereas the group of horses and riders was fairly diverse. The latter can be considered both a limitation and a benefit, on one hand it introduces more random variation, on the other hand it supports the generalisation of significant findings to a larger population. The exercise program was constructed for this study (but emanated from training concepts used by the trainer, author HE, at the time). The goal of the study was that each horse and rider should achieve the best results possible there and then, if needed with verbal support from the trainer. Only the (subjectively) best performance achieved within the trial was used in the analysis to ensure that only high-quality data were analysed (in some trials some exercise sequences were deemed insufficient, resulting in missing data). The strict criteria for selecting exercise sequences resulted in that statistical power was lower for the lateral exercises and the highest degrees of collection, because there were fewer good strides available for these exercises. The timing variables were expressed as percentages of the cyclic gait motion, yielding data that were not optimally normally distributed. Thus, these parameters fitted the regressions less well, even if deemed to have an acceptable fit. The chaotic withers trace was problematic to analyse. In future research on collection and lateral exercises we suggest high-speed video capturing of midline markers placed on a larger number of anatomical positions to shed further light on the vertical forehand movement during riding. To include measurements on straight line in addition to circles would also be an asset.

The riders were given a questionnaire to determine the horses' hollow side, still from the answers sidedness was somewhat difficult to determine. The hollow side was added as a fixed factor to the ROM models (both cannons and midline variables, Supplementary Results S1) but no relevant significant effects were found. To address the questions of objective and subjective 'biomechanical' laterality during training, a large number of horses need to be evaluated and better methods for determining sidedness at training likely need to be developed (Byström *et al.*, 2019). Further, it was outside the scope of the study to investigate effects of interactions between left-right asymmetries in horses and in riders.

5. Conclusions

This study is the first to describe collection and lateral exercises in ridden walk on the circle. Fore- and hind limb cannon protraction-retraction ROM and S1 vertical ROM decreased with increasing degree of collection, suggesting

that the riders achieved a shortening of the gait. In shoulder-in and haunches-in, the diagonal oriented in the direction of motion showed decreased hind limb cannon ROM while forelimb cannon ROM was maintained; this could be related to the equestrian goals of lateral exercises, increased shoulder freedom and collection of the targeted diagonal.

Supplementary material

Supplementary material can be found online at <https://doi.org/10.3920/CEP210019>.

Figure S1. Time-normalised stride data for the S1 vertical displacement data by exercise, in left (upper row) and right (lower row) directions on the circle for one horse.

Figure S2. Time-normalised stride data from one trial for left (inner) fore- and right (outer) hind (upper row) and right (outer) fore- and left (inner) hind (bottom row) cannon pitch angles in walk on the circle in left direction.

Table S1. Questions asked about horse laterality during riding, the last column containing the interpretation.

Table S2. Distribution of number of selected strides by exercise. N denotes number of trials with data in this exercise. Trials (n=21) with only one stride each were deleted from the cannon pendulation analyses.

Results S1. Data, code and output used in the statistical analysis.

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Conflict of interests

None of the authors have any conflicting interests.

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